

SHORT-HARD GAMMA-RAY BURSTS IN YOUNG HOST GALAXIES: THE EFFECT OF PROMPT TWINS

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ABSTRACT

We investigate the effect of including a significant “binary twin” population (binaries with almost equal mass stars, $q = M_2/M_1 \gtrsim 0.95$) for the production of double compact objects and some resulting consequences, including LIGO inspiral rate and some properties of short-hard gamma-ray bursts. We employ very optimistic assumptions on the twin fraction ($\sim 50\%$) among all binaries, and therefore our calculations place an upper limits on the influence of twins on double compact object populations. We show that for LIGO the effect of including twins is relatively minor: although the merger rates does indeed increase when twins are considered, the rate increase is fairly small (~ 1.5). Also, chirp mass distribution for double compact objects formed with or without twins are almost indistinguishable. If double compact object are short-hard GRB progenitors, including twins in population synthesis calculations does not alter significantly the earlier rate predictions for the event rate. However, for one channel of binary evolution, introducing twins more than doubles the rate of “very prompt” NS-NS mergers (time to merger less than 10^6 years) compared to models with the “flat” q distribution. In that case, 70% of all NS-NS binaries merge within 10^8 years after their formation, indicating a possibility of a very significant population of “prompt” short-hard gamma-ray bursts, associated with star forming galaxies. We also point out that, independent of assumptions, fraction of such prompt neutron star mergers is always high, $\sim 35 - 70\%$. We note that recent observations (e.g., Berger et al.) indicate that fraction of short-hard GRBs found in young hosts is at least $\sim 40\%$ and possibly even $\sim 80\%$.

Subject headings: binaries: close — black hole physics — gravitational waves — stars: evolution — stars: neutron

1. INTRODUCTION

A majority of stars are in binaries, and a substantial fraction of binaries have short enough orbital periods that they are likely to interact during either their main sequence or post-main sequence evolution. Many of the most interesting phenomena in astronomy can be directly traced to the interaction of close binaries; an incomplete list would include binary neutron stars and white dwarfs, supernovae Ia, cataclysmic variables, and blue stragglers. There is a vast literature on the subject (e.g., Paczynski 1971; Wellstein & Langer 1999; Hurley, Tout & Pols 2002; Belczynski, Kalogera & Bulik 2002b). Although there are many ingredients that must be considered in interacting binaries, an implicit assumption in much theoretical work has been that the lifetimes of the stars are almost always quite different. This assumption arises naturally from two considerations. First, the single star initial mass function (IMF) is a steep function of mass, with low mass stars being far more numerous than high mass stars (e.g. Salpeter 1955), and strong mass-lifetime relationship for all but the most massive stars implies a large lifetime difference unless the masses are very close. Second, a flat mass ratio spectrum (see for example Kuiper 1935) for binaries that are likely to interact is adopted in most population synthesis studies, leading to very few “equal” component mass binaries.

Pinsonneault & Stanek (2006) have argued that obser-

vations indicate the existence of a substantial population of nearly equal mass binaries (“twins”). In such systems a strong inequality in lifetime is not present, so there might be important qualitative differences in their evolution compared to unequal mass binaries. Survey of astronomical literature strongly suggests binary twins are a general feature of close binary population, as a peak near $q = 1$ was reported by a number of investigators. For example, Halbwachs et al. (2003) studied a large sample of spectroscopic binaries type F7 to K (masses from about 1.7 down to 0.5 M_\odot), including binaries in open clusters. They find that the mass ratio has a broad peak from $q \approx 0.2$ to $q \approx 0.7$, and a sharp peak for $q > 0.8$. As they discuss, the strength of the peak for $q > 0.8$ gradually decreases with the increasing orbital period, which is to be expected. The fraction of twins can be as high as 50% for periods $P < 10$ days and it is still significant (as high as 35%) for much longer periods of up to 1000 days. A much earlier study by Lucy & Ricco (1979) also finds a strong and narrow peak of binaries with $q \approx 0.97$, again using a sample of spectroscopic binaries corrected for various observational errors and biases. Tokovinin (2000) confirms that finding using additional data and in fact also calls this population “twins”, arguing that they constitute 10-20% of the total binary population in the $P = 2 - 30$ days regime.

Additional, although perhaps more anecdotal support for the significant twin population comes from the realm of very high mass stars found in eclipsing binaries. The

most massive binary known, WR 20a (Rauw et al. 2004; Bonanos et al. 2004), is an eclipsing system, so the masses of both components can be measured accurately. The masses are $83 M_{\odot}$ and $82 M_{\odot}$ (Rauw et al. 2005), giving a mass ratio of $q = 0.99$. Given that $80 M_{\odot}$ stars are extremely rare (both due to the steepness of the mass function and their short lifetime), having such extremely massive secondary would be quite unlikely unless the twin phenomenon is involved.

There are also some theoretical considerations that seem to indicate that double neutron star binaries form *only* from twins (Bethe & Brown 1998; Chang-Hwan, Hong-Jo & Brown 2007). If this is the only double neutron star formation scenario, the twin fraction must be high to explain the observed rates of these binary systems.

However, not all evidence points towards a large population of twins. First, there are some loopholes to the arguments pushing toward the theoretical requirement of twins to make double neutron star systems. In addition, the existence of low-mass X-ray binaries requires some systems with very different masses (Kalogera & Webbink 1998; Fryer, Burrows & Benz 1998). Even with the intermediate-mass progenitors of these low-mass X-ray binaries (Podsiadlowski, Rappaport & Pfahl 2002), a large twin fraction coupled on top of a otherwise flat mass ratio distribution would have trouble explaining low-mass X-ray binaries. Finally, not all the observational evidence points toward a twin fraction. Kobulnicky & Fryer (2007) argue that for their dataset of 120 O and early B stars, the twin fraction must be less than 25%. Their study used one of the largest datasets of O and early B stars focusing on a single stellar association - Cygnus OB2 (Kiminki et al. 2007).

With observations and theory arguing both for and against twins, we investigate the effect of twin binaries on population of close (coalescing within Hubble time) double compact objects, focusing on observations that might allow us to distinguish a twin population of stars from the more standard stellar mass ratio distributions. In this study we present the population synthesis study of double neutron star (NS-NS), black hole neutron star (BH-NS) and double black hole (BH-BH) progenitors. We employ two basic calculations; one with the usually adopted flat mass ratio distribution and one that includes a very large (50%) population of twins. The results are discussed in context of double compact object mergers that are expected to be the prime sources of gravitational radiation for ground based observatories like LIGO or VIRGO (e.g., Kalogera et al. 2007), and are also considered as very likely short-hard gamma ray burst progenitors (Nakar 2007). In a forthcoming paper (Belczynski & Pinsonneault, in prep.) we will study the influence of twins on lighter compact object binaries with white dwarfs and their connection to Type Ia supernovae and formation of blue stragglers.

2. MODEL

2.1. Population synthesis model

Binary population synthesis is used to calculate the merger rates and properties of double compact objects. The population synthesis code employed in this work, **StarTrack**, was initially developed for the study of double compact object mergers in the context of gamma-ray burst (GRB) progenitors (Belczynski, Bulik & Rudak 2002a)

and gravitational-wave inspiral sources (Belczynski et al. 2002b). In recent years **StarTrack** has undergone major updates and revisions in the physical treatment of various binary evolution phases, and especially mass transfer phases. The new version has already been tested and calibrated against observations and detailed binary mass transfer calculations (Belczynski et al. 2007a), and has been used in various applications (e.g., Belczynski, Bulik & Ruiter 2005; Belczynski et al. 2006; Belczynski et al. 2007b). The physics updates that are most important for compact object formation and evolution include: a full numerical approach to orbital evolution due to tidal interactions, calibrated using high mass X-ray binaries and open cluster observations, a detailed treatment of mass transfer episodes fully calibrated against detailed calculations with a stellar evolution code, updated stellar winds for massive stars, and the latest determination of the natal kick velocity distribution for neutron stars (Hobbs et al. 2005). For helium star evolution, which is of a crucial importance for the formation of double neutron star binaries (e.g., Ivanova et al. 2003; Dewi & Pols 2003), we have applied a treatment matching closely the results of detailed evolutionary calculations. If the helium star fills its Roche lobe, the systems are examined for the potential development of a dynamical instability, in which case they are evolved through a common envelope (CE) phase, otherwise a highly non-conservative mass transfer issues. We treat CE events using the energy formalism (Webbink 1984), where the binding energy of the envelope is determined from the set of helium star models calculated with the detailed evolutionary code by Ivanova et al. (2003). The progenitor evolution and the Roche lobe overflow episodes are now followed in much greater detail. We note significant differences from our earlier studies. For a detailed description of the revised code we refer the reader to Belczynski et al. (2007a).

2.2. Recent model revisions

The most recent and important changes in the context of double compact object formation reflect the treatment of the dynamically unstable mass transfer and evolution into the CE phase. First, it was pointed out that there is only (if any) a small chance of survival of CE phase if a donor star is on the Hertzsprung gap (HG), simply because there is no clear entropy jump between core and envelope so once CE inspiral is initiated it does not stop until the two binary components coalesce (see Belczynski et al. 2007b). Second, we limit accretion onto compact objects during CE phase to 10% of the Bondi-Hoyle rates based loosely on estimates of outflows (Armitage & Livio 2001). We have also slightly modified our input physics in context of rejuvenation, black hole spin (Belczynski et al. 2007c) evolution and debugged the entire code.

2.3. Calculations

Two separate evolutionary models for massive star binaries are calculated. They differ only in common envelope treatment. In one calculation (model A) that we will refer to as our reference model we do not allow for common envelope survival in case the donor star is crossing HG. This is in effect for H-rich HG stars as well of helium HG stars. The former reduces drastically formation (and

merger) rates of BH-BH binaries, while the later reduces moderately rates for NS-NS systems as discussed in detail by Belczynski et al (2007b). In alternative common envelope model (model B) we allow for CE survival for all donors (HG included). It does not mean that system can survive every CE phase. The regular standard energy balance (e.g. Webbink 1984) is performed to check for a potential survival. In both models we vary an assumption on the initial mass ratio (lower-mass over higher-mass binary component) of binaries that we evolve. We either employ flat mass ratio distribution and we will refer to these populations as “flat” binaries or we impose “twin” distribution in which we require that 50% binaries have mass ratio distributed uniformly in range $q = 0.95 - 1.0$ while the remaining 50% have flat distribution for $q = 0.0 - 0.95$. For each models we evolve $N_{\text{tot}} = 1.465 \times 10^6$ binaries with solar metallicity ($Z = 0.02$). We require that the primary mass is drawn from power-law IMF with slope -2.7 , while secondary mass is obtained through a given mass ratio distribution. We additionally require that the primary initial mass is $6 > M_1 > 150 M_\odot$ while secondary initial mass is $4 > M_2 > 150 M_\odot$. The range of masses was chosen such that it encompasses entire possible mass range for double compact object formation. In particular, low-mass ends take into account potential rejuvenation of stars through binary accretion. To initialize our populations we first draw a primary mass, then mass ratio is drawn from a given distribution, and then mass of a secondary is calculated from $M_2 = q \times M_1$. If M_2 is smaller than required minimum mass ($M_2 = 4 M_\odot$) we repeat the drawing. Such a scheme, although it uses underlying flat mass ratio distribution results in skewed (toward high- q) distribution. The resulting initial mass ratio distributions are presented in Figure 1 (top panel).

2.4. Calibration

For calibration and Galactic compact object merger rate calculation we use binary fraction of $f_{\text{bi}} = 0.5$, and we assume that star formation rate (SFR) was constant in Galaxy through last 10 Gyr at the level of $3.5 M_\odot \text{ yr}^{-1}$. To calculate the synthetic SFR we extend our IMF down to hydrogen burning limit ($0.08 M_\odot$), with a three component broken power-law IMF with slopes of $-1.3 / -2.2 / -2.7$ and corresponding breaks at $0.5 M_\odot$ and $1.0 M_\odot$ (Kroupa & Weidner 2003). For our twin populations we assume that twin binaries are formed independent of binary properties (like period) and that they form in entire mass range ($0.08 > M > 150 M_\odot$). The mass of entire underlying stellar population (all single and binary stars) that corresponds to our simulations (F_{sim}) is $7.729 \times 10^8 M_\odot$ and $6.182 \times 10^8 M_\odot$ for flat and twin populations, respectively. Since the star forming mass in Galaxy is $F_{\text{sfr}} = 3.5 \times 10^{10} M_\odot$ it results in calibration boost factors ($F_x = F_{\text{sfr}}/F_{\text{sim}}$) of $F_x = 45$ and 57 for flat and twin populations, respectively. After evolution of massive primordial binaries ($N_{\text{tot}} = 1.465 \times 10^6$) we obtain population of double compact objects in each model. Then in a given model we initiate each double compact object F_x times at different starting time. Starting times are chosen from the uniform distribution within the range of $0 - 10$ Gyr (constant SFR). The starting time is then increased by an evolutionary time that was needed for a progenitor binary to form a given double compact object

($T_{\text{evol}} \sim 10 - 20$ Myr). The double compact objects are then evolved with angular momentum losses due to emission of gravitational radiation until they merge. Merger times are denoted as T_{mer} and they can span a wide range of values. The entire lifetime of a given binary is then $T_{\text{life}} = T_{\text{evol}} + T_{\text{mer}}$. We record the time at which they merge. Then we calculate an average merger rate in period $0 - 10$ Gyr. These are our predicted Galactic merger rates. It is worth to note three things.

First, it may seem counter-intuitive that the boost factor is larger for (more massive) twin population. However, one needs to realize that in the population of stars of a given mass there is a larger number of high mass binaries ($6 > M_1 > 150 M_\odot$ and $4 > M_2 > 150 M_\odot$) in twin population as compared with flat population. Simply, it is easier to form both binary components with high masses in a population with mass ratio peaked at high values (twins) as opposed to population with flatter mass ratio distribution. As we have evolved the same number of twins and flat high mass binaries, it means that the number of stars in an entire underlying stellar population ($0.08 - 150 M_\odot$) is smaller for twins than for flat binaries. Finally, since the most mass is contained in primaries and single stars, and not in secondaries (that are heavier in twin population), it translates into a smaller mass of underlying stellar population containing twin binaries. Smaller the simulated mass (F_{sim}) higher the boost factor.

Second, we have employed an optimistic (pro-twin) approach, as we do not put any period constraints on twin formation (see § 1 discussing evidence that twins may form preferentially at short periods) in addition to adopting a very high fraction of twins (50%). Had we limited population of twins, the boost factor F_x for twins would decrease, making the differences between twin and flat calculations less pronounced.

Third, since, we also consider population of ultracompact (extremely short-lived) double neutron star binaries it is important to notice their increased contribution to merger rates. If at formation there are similar in size populations of short- and long-lived double compact objects, the short-lived systems will dominate merger rates. Long-lived systems merge beyond our counting time of 10 Gyr (age of the disk) unless they happen to form early on, while short-lived systems contribute to merger rate independent of their formation time (provided that their merger times are much shorter than the age of the disk).

3. RESULTS

3.1. Rates

First we have calculated Galactic merger rates for the two models and we have translated them into advanced LIGO detection rates using method presented in Belczynski et al. (2007b). The results are presented in Table 1.

The Galactic merger rates of double compact objects (combined for NS-NS/BH-NS/BH-BH) for flat populations are $13 - 48 \text{ Myr}^{-1}$ while for twin populations $20 - 74 \text{ Myr}^{-1}$. The range of the rates corresponds to our different assumption on CE evolution and formation (or lack of thereof) of ultracompact NS-NS systems as was discussed in detail by Belczynski et al. (2007b). The factor of ~ 1.5 increase in rates from flat to twin dominated populations is equally connected to (i) the difference in underlying star

population that gives boost factor $\sim 25\%$ larger for twins than for flat binaries (see SFR calibration § 2.4) and (ii) the slightly higher ($\sim 20\%$) formation efficiency of double neutron stars from massive twin binaries. The small magnitude of the later effect may be somewhat surprising, as one would intuitively expect that with the twin population production of double compact objects would significantly increase. In the following we explain this surprising finding.

First, we examine the mass ratio distribution of flat population for model A. There is a significant fraction ($\sim 40\%$) of massive binaries that we have evolved with low mass ratios ($q_{\text{init}} < 0.65$; Fig.1; top panel). On the other hand, binaries that actually produce double compact objects (Fig.1; middle panel) are found predominantly with high mass ratios but in a rather wide range ($q_{\text{init}} \sim 0.65 - 1$). Note that there is no significant peak for double compact object progenitors at high- q_{init} . Second, if we go from flat to twin population we shift half of the initial binaries from the entire mass ratio range to the very high mass ratios (Fig. 1; top panel). Binaries that are shifted from the low- q range ($\sim 20\%$ of the population) will become an extra component in formation of double compact object in twin population. Binaries that are shifted from the high- q range will produce double compact objects but will not increase the overall production rate since they would have formed double compact objects anyway. Therefore, the rate increase factor from the shift of binaries from standard to twin population is only $\sim 20\%$.

The above finding is a direct result of the shape of the mass ratio distribution of double compact object progenitors. In model A for the flat population mass ratio is found within range $q_{\text{init}} \sim 0.5 - 1$ and it falls slowly with the decreasing q_{init} . The lack of progenitors below $q_{\text{init}} \sim 0.5$ is connected to fact that below that value the progenitor binary evolves through common envelope (rather than stable mass transfer phase) after primary evolved of main sequence, and the CE leads most often to a merger. This is especially true since most of the donors will start mass transfer on Hertzsprung gap as during this phase stars experience maximum radial expansion (Belczynski et al.2007b).¹ The slope of the distribution is explained by the narrow range of masses in which double neutron stars form (and since they dominate double compact object population they set the distribution). If a primary is chosen within a range for NS formation ($\sim 8 - 20 M_{\odot}$) it is easier to find potential secondary that can form NS if mass ratio is higher. If mass ratio is too small, the primary have a greater chance to have mass below NS formation mass, and therefore mass ratio distributions falls off with decreasing q_{init} . Intrinsically, once two stars have masses within NS formation range and their mass ratio is over 0.5, there is no preference for NS-NS formation at higher q . In other words, we do not note any significant evolutionary effects that make it easier to make NS-NS at high mass ratio.

Advanced LIGO detection rates are listed in Table 1. As for Galactic merger rates there is a range of values for flat population: $15 - 700 \text{ yr}^{-1}$ and for twin population $22 - 825 \text{ yr}^{-1}$. And as before the range corresponds to the change

on assumption on CE evolution. However, the increase in rates from model A to B is now due to the increased formation of BH-BH binaries in model B. These binaries, although a small contributor to Galactic merger rates, are most important for LIGO as they can be detected from much larger distances (much higher chirp masses) as compared to NS-NS mergers and therefore they dominate detection rates (see also Belczynski et al. 2007b). We note that the change of the detection rates for LIGO from flat to twin population is rather small (factor of ~ 1.5) and is much smaller than other model uncertainties (e.g. CE evolution).

3.2. Double compact object chirp mass

In Figure 2 we show the distribution of chirp mass for coalescing double compact objects. As the population of double compact objects is dominated by double neutron stars we see that the distributions peak at $\sim 1.2 M_{\odot}$ that corresponds to the typical chirp mass of a 1.35 and $1.35 M_{\odot}$ NS-NS binary (see also Belczynski et al. 2007d). We also note that the distributions are almost the same for the flat and twin populations. This is the result of the underlying initial final-mass relation (see Belczynski et al. 2007a for details). This relation shows that neutron stars form with the similar mass ($\sim 1.35 M_{\odot}$) for a wide range of progenitor masses $M_{\text{zams}} \sim 8 - 18 M_{\odot}$ and only in the narrow range $M_{\text{zams}} \sim 18 - 20 M_{\odot}$ heavier neutron stars ($\sim 1.8 M_{\odot}$) are formed. Such the initial-final mass relation leads to a rather narrow distribution of neutron star masses (somewhat widened by accretion and mass loss in binaries) that is obtained in both populations. If the two populations are compared in context of the flat initial-final mass relation it becomes obvious why the two distributions peak at the same value. For flat population two neutron star progenitors are found (on average) farther apart in mass than for twins but still they need to fall within the narrow mass limits that allow neutron star formation ($M_{\text{zams}} \sim 18 - 20 M_{\odot}$). For twin model the two progenitors are closer in mass, but still are within the same mass limits. Since the mass of a neutron star does not depend strongly on the initial mass of progenitor the masses of neutron stars in both models are similar. There are other heavier compact objects, namely black hole neutron star systems and double black hole systems with chirp masses reaching all the way to $\sim 10 M_{\odot}$, both for twin and flat populations. In particular we find many more heavier systems in model B as in this model black hole systems form with much higher efficiency as compared to model A (Belczynski et al. 2007b).

3.3. Merger times

Merger time distributions for flat and twin double compact object binaries are presented in Figure 3. In the top panel we show calculations with our reference evolutionary model, while the bottom panel demonstrates results for the alternative common envelope evolution. For the reference model the two distributions are very similar, and the number of mergers falls off rapidly with the decreasing merger time. However, we still predict quite a significant number of double compact objects: $\sim 35\%$ with merger

¹We can see that if we relax our assumption on CE mergers in model B (Fig.1, bottom panel) the mass ratio of double compact progenitors extends to low- q_{init} values.

times shorter than 100 Myr. Most of these short lived systems are double neutron stars that have formed along evolutionary channels that end in the stable mass transfer episode with a helium star donor (e.g., Ivanova et al. 2003). In the model with alternative evolution we allow for common envelope survival even if donor stars are crossing Hertzsprung gap. Although this may appear not to be supported by the current understanding of inspiral process (see § 2 and Belczynski et al. 2007b for more through discussion) the common envelope evolution and the associated inspiral is not yet fully understood. Distributions are similar for flat and twin binaries for high merger times. However, for small merger times there is an additional component in both distributions as compared to the standard calculations. Moreover, this additional component is much more pronounced in twin population than in flat population. In particular we find that in flat population this component ($T_{\text{mer}} \lesssim 1$ Myr) contains 33% of mergers while in twin population it reaches 50%. Accounting for the shape of distribution and the larger number of mergers in twin population it translates to ~ 2.5 times as many short-lived systems in twin population as compared to flat population. The systems with very short merger times ($T_{\text{mer}} \lesssim 1$ Myr) are so called "ultracompact" double neutron stars, that form through one extra common envelope phase (additional orbit contraction) as opposed to standard model binaries with larger merger times (e.g., Belczynski et al. 2002b; Ivanova et al. 2003; Belczynski et al. 2006).

In Table 1 we list fractions of prompt double compact object mergers. These will include potential short-hard GRB progenitors: NS-NS and BH-NS mergers. Although, it is noted again that these fractions are almost completely dominated by NS-NS mergers. Fractions are given for binaries that have lifetimes ($T_{\text{evol}} + T_{\text{mer}}$) shorter than 100 (F_{100}) and 1000 Myr (F_{1000}). We find that in the reference model $\sim 35\%$ of the mergers are expected to occur in young hosts (with stellar populations as young as 100 Myr) both for flat and twin models. However, if alternative evolution is included in calculations, then the fraction increases to 60% for flat population and to 70% for twin population. This is a direct result of merger time distribution that is similar for twin and flat population in the reference model (see Fig. 3 top panel) and different for alternative CE model, in particular twins producing many more ultracompact NS-NS binaries (see Fig. 3 bottom panel).

The fractions of the mergers are also given in Table 1 for significantly older (but still rather young) hosts: 1000 Myr. It is found that great majority of the mergers $\sim 70\%$ and $\sim 80\%$ for reference and alternative CE models is then expected to take place in hosts of this age. At this age (or lifetime of the double compact object population) the ultracompacts are not so important as the classical long-lived systems play an important role in overall population and the fractions are rather independent of whether twin or flat populations are considered (see Fig. 3).

In the following we explain the more effective production of ultracompacts in the twin population than in the flat population for alternative CE evolution (see Fig. 3; model B). We will limit the discussion to double neutron stars and their progenitors as they constitute the vast majority

($\sim 99\%$) of double compact object (DCO) systems with ultrashort merger times (i.e., $T_{\text{mer}} < 1$ Myr). The distribution of initial mass ratio for progenitors of ultracompact DCOs is presented in Figure 4.

For the flat population (see Fig. 4, top panel) we notice that (i) in model A there are rather few progenitors with high mass ratios ($q_{\text{init}} = 0.95 - 1$) in contrast to model B in which we find a prominent peak of the distribution at high mass ratios. Therefore for model B, redistribution of progenitors from the flat to twin mass ratio distribution is enhancing the production of ultracompacts. In fact, for twin population (see Fig. 4, bottom panel) we observe an increase of ultracompact systems by a factor of ~ 2.5 in model B (see the significant increase of these systems at high- q_{init}). Note that the change of the mass ratio distribution from flat to twin increases number of progenitors due to the calibration (see § 2) but this increase factor is only ~ 1.2 . The additional increase is solely due to the peak in the number of high- q_{init} systems for model B ultracompacts.

The shape of the mass-ratio distribution for progenitors of ultracompact systems is understood in the framework of evolution of massive stars leading to the formation of double neutron stars. In general, classical (long-lived) NS-NS binaries form from progenitors that experience only two mass transfer episodes. The ultracompact systems progenitors usually go through an additional mass transfer episode. This third mass transfer episode is encountered just before second NS formation. A low-mass helium star overfills its Roche lobe and starts transferring He-rich material to the first born NS. Most often such a transfer occurs when a helium star is crossing Hertzsprung gap (large radial expansion). Depending on the mass ratio and the evolutionary stage of the helium donor (where on HG) the mass transfer is either stable or it evolves into CE phase. Since the most of the neutron stars in our simulations have mass $1.3 - 1.4 M_{\odot}$ the mass ratio is set by the mass of helium donor. For very light helium stars ($\sim 3 M_{\odot}$), stable mass transfer is predicted while, for more massive donors ($\gtrsim 3.5 M_{\odot}$), a CE develops. The mass of the helium star is set predominantly by the initial mass of the progenitor star (in addition to mass gain and loss in earlier binary interactions); the lower the mass of the progenitor, the lower mass of helium star it forms. Since the helium star is formed out of secondary (most cases) and q_{init} was defined as the ratio of the mass of secondary to primary, it is expected that systems going through the stable mass transfer (lower mass helium star progenitor) have initially a lower mass ratio than systems developing CEs (higher mass helium star progenitor).

In model A we do not allow for CE survival if donor is on HG and therefore progenitors with very high mass ratios are disfavored. In model B, that allows for survival of the CE phase with the HG donor, the high mass ratio progenitors are abundant and they contribute to formation of ultracompacts. Additionally, the higher mass ratio systems are more likely to survive initial mass transfer episodes in the evolution of progenitor binary (e.g., closer in mass components so lower the probability of a merger during CE phase).

4. COMPARISON WITH EARLIER STUDIES

Bethe & Brown (1998) proposed a scenario of double neutron star formation from twin binaries. In this scenario, because the two stellar components of the binary are nearly equal mass, the system undergoes both common envelope phases prior to the collapse of either star. In such a scenario, the neutron stars formed in collapse need not undergo a CE phase, and hence avoid accreting additional material. This model provides a natural explanation for double neutron star systems in which both neutron stars had nearly equal masses. But it only works when the two binary components have nearly equal mass, and hence, strongly depends on the number of twins. Bethe & Brown (1998) and subsequent work by Lee et al. (2007) argue that this scenario can explain all of the NS-NS binary systems observed if a large twin population exists. They argue that any formation scenario that forces a neutron star to go through a common envelope phase will produce a low-mass black hole, not a neutron star. The bulk of the simulations by Fryer, Woosley & Hartmann (1999) also made this assumption, and came up with similar conclusions: with appropriate choices of the other free parameters, one can match the observed NS-NS systems.

But whether or not this scenario is the dominant formation path for double neutron star binaries hinges on the fact that the accretion onto a neutron star in a common envelope system is equal to the Bondi-Hoyle rate. Recall that it was realized that neutrino cooling would allow the neutron star to accrete beyond the Eddington rate, causing the neutron star to accrete as much material as is fed it. If one assumes this rate is equal to the Bondi-Hoyle rate, the accretion can be up to a solar mass. But the actual accretion rate may be much less. First, how much one accretes depends sensitively on the evolution of the common envelope phase (Fryer et al. 1999). Very few simulations have focused particularly on neutron stars in stellar mergers with giant companions. Most examples have very rough boundary conditions and/or do not model the inspiral of a neutron star in a massive companion (e.g. Ruffert 1999; Armitage & Livio 2000; Zhang & Fryer 2001; Ricker & Taam 2007). This preliminary work has yet to solve the actual merger process. But these studies have determined a few key issues with the Bondi-Hoyle assumption in neutron star accretion in stellar inspiral: density/velocity gradients can alter the Bondi-Hoyle accretion at large scales, density/velocity gradients can lead to disk formation and outflows.

Ruffert & Anzer (1995), Ruffert (1999) and Taam & Ricker (2007) have focused on the deviation at large scales of the Bondi-Hoyle accretion rate. At issue here is that angular momentum in the accreting material can provide pressure support for the infalling material, slowing the accretion. Fryer et al. (1996) calculated values for the density and velocity gradients and compared these results with those of Ruffert & Anzer (1995) and found that this pressure support on the global scale was minimal ($< 40\%$ level for quite large velocity gradients). Since this time, Ruffert (1999) studied the same effect under density gradients. Again, if we use the estimates from Fryer et al. (1996) for the density gradients in $10, 20 M_{\odot}$ supergiants, we expect 10-20% variations away from the accretion rate predicted by the Bondi-Hoyle formalism. This only changes as the neutron star spirals near the inner edge of the hydrogen

envelope, where density gradients can become quite large.

Fryer, Benz & Herant (1996) assumed that as long as Bondi-Hoyle accretion were unaffected, the angular momentum would somehow be transported outward, allowing the material to accrete onto the neutron star. But subsequent studies are showing that this assumption may well be incorrect (Armitage & Livio 2001; Fryer et al. 2006; Fryer 2007). Armitage & Livio (2001) showed that the angular momentum in the inflow would lead to disk formation, and ultimately, an outflow that could halt accretion. If the material is unable to get rid of the energy produced by viscous interactions, an outflow is bound to occur (Blandford & Begelman 1999). Fryer et al. (2006) and Fryer (2007) have specifically studied accreting neutron star systems and found that even a small amount of angular momentum would lead to outflows. In these low-angular momentum flows, the outflows decreased the accretion rate by 50%, but for the high-angular momentum flows in CE phases, the outflow could decrease the accretion by more than an order of magnitude (Blandford & Begelman 1999). Because of such results, we estimate our mass accretion by assuming an accretion rate of 10% the Bondi-Hoyle rate. It could even be an order-of-magnitude lower.

This reduced accretion rate allows additional scenarios for forming double neutron star systems which can also be shown to match the current observations of double neutron star systems (this study; Belczynski et al. 2007d). It also avoids any problems over-producing (or hiding) the number of massive NS-NS systems. Brown & Bethe (1998) turned these systems into low-mass BH-NS systems by requiring a maximum neutron star mass between $1.7-1.8 M_{\odot}$. However, observations may indicate that the maximum neutron star mass is $M_{\text{ns,max}} \sim 2 M_{\odot}$ (e.g., Ransom et al. 2005; Barziv et al. 2001) while some theoretical work allows for equation of states with $M_{\text{ns,max}} \sim 2 - 3 M_{\odot}$ (e.g., Morrison, Baumgarte & Shapiro 2004). If these systems form black holes, we also do not see the low-mass black holes in the Galaxy - all black holes in the Galaxy have masses above $\sim 3 M_{\odot}$ (Orosz 2003; Cesares 2007), although Fryer & Kalogera (2001) argued that this is more likely the result of observational biases. Additionally, this new accretion estimate agrees very well with the amount of matter that is needed to mildly recycle a pulsar (Zdunik, Haensel & Gourgoulhon 2002 on theoretical calculations; Jacoby et al. 2005 on observational estimate).

This is not to say that the Brown scenario requiring twin binaries does not contribute to the double neutron star population. But in our scenario with the reduced accretion rate, it is simply not the dominant formation scenario. Because of this, our results are much less sensitive to the size of the twin population.

5. DISCUSSION

Our calculations discussed in this paper involved a very simple twin scenario, i.e. half of all the binaries were postulated to be equal mass ($q > 0.95$). In reality, the true fraction of twins is likely to depend on the mass of the primary, most certainly on the orbital separation of the two stars, and also possibly on the metallicity of stars. Indeed, even the actual binary fraction is likely a function of primary mass (e.g., Lada 2006). There was a recent report

that the fraction of B-type binaries in the LMC might be significantly lower than in our Galaxy (Mazeh, Tamuz & North 2006), indicating a possibility of strong metallicity dependence in the efficiency of binary formation.

From the absolute rates point of view, we show that effect of including twins is relatively minor: although the merger rate does indeed increase when twins are considered, the rate increase is fairly small (~ 1.5). This is the direct result of evolutionary calculations that provide numerous channels of NS-NS formation without a strong preference for the high mass ratio of progenitor binaries. The same calculations recover the empirically estimated rates of double neutron star mergers as some of their observed properties (Belczynski et al. 2007d). Also, chirp mass distribution for double compact objects formed with or without twins are almost indistinguishable. If double compact object are short-hard GRB progenitors, including twins in population synthesis calculations does not alter significantly the earlier rate predictions for the event rate.

Nevertheless, there are some interesting changes when we include significant twin population. For one channel of binary evolution that allows ultracompact binaries, introducing twins doubles the rate of very prompt NS-NS mergers (time to merger less than 10^6 years) compared to models with the “flat” q distribution. In that specific case, $\sim 70\%$ of all NS-NS binaries would merge within 10^8 years after their formation (see Table 1), indicating a possibility of a very significant population of short-hard gamma-ray bursts associated with star forming galaxies. We should mention that twins are not necessary to have a significant prompt population of NS-NS binaries. Even

using most conservative assumptions, $\sim 35\%$ of all NS-NS binaries merge within 10^8 years after their formation (See Table 1). This is very interesting because of the well localized short-hard bursts, roughly 40% occurred in young hosts, 15% in old hosts, and location of roughly 45% is still unknown (Berger et al. 2007; E. Berger, private communication). So not only are the “prompt” short-hard GRBs very common, they might turn out to be the majority of this class of bursts, as the rough current limits are from 40% to even 85%.

The fact that so many short-hard burst are found in star-forming galaxies may have far reaching consequences for our understanding of binary evolution (if indeed short-hard GRBs are connected to double compact object mergers). If further observations find that even higher fraction of short-hard GRBs is in young galaxies, that will indicate strongly that the ultracompact channel of the binary evolution does indeed lead to double compact object formation, something that otherwise is very hard to resolve observationally. If that fraction is higher still, i.e. 70% and above, we will not only need the ultracompact channel to be allowed, we might also need a significant binary twin population to explain such a high rate (see Table 1). Needless to say, more observational constraints on short-hard GRBs and their hosts are needed here.

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TABLE 1
DOUBLE COMPACT OBJECTS: FLAT (TWIN) POPULATIONS^a

Model ^b	R_{Gal} [Myr ⁻¹]	$R_{\text{A,ligo}}$ [yr ⁻¹]	F_{100} [%]	F_{1000} [%]	Comments
A	13 (20)	15 (22)	38 (36)	72 (72)	reference model
B	48 (74)	692 (825)	60 (71)	83 (88)	HG CE allowed

^aValues are given for calculations that account either for flat or twin (in parenthesis) initial mass ratio distribution.

^bWe list Galactic merger rates (R_{Gal}) and advanced LIGO detection rates ($R_{\text{A,ligo}}$) for all double compact objects, while fractions of mergers (F_{100} , F_{1000}) that take place in young galaxies (< 100 , < 1000 Myr, respectively) are given only for potential GRB progenitors (i.e., NS-NS and BH-NS mergers).

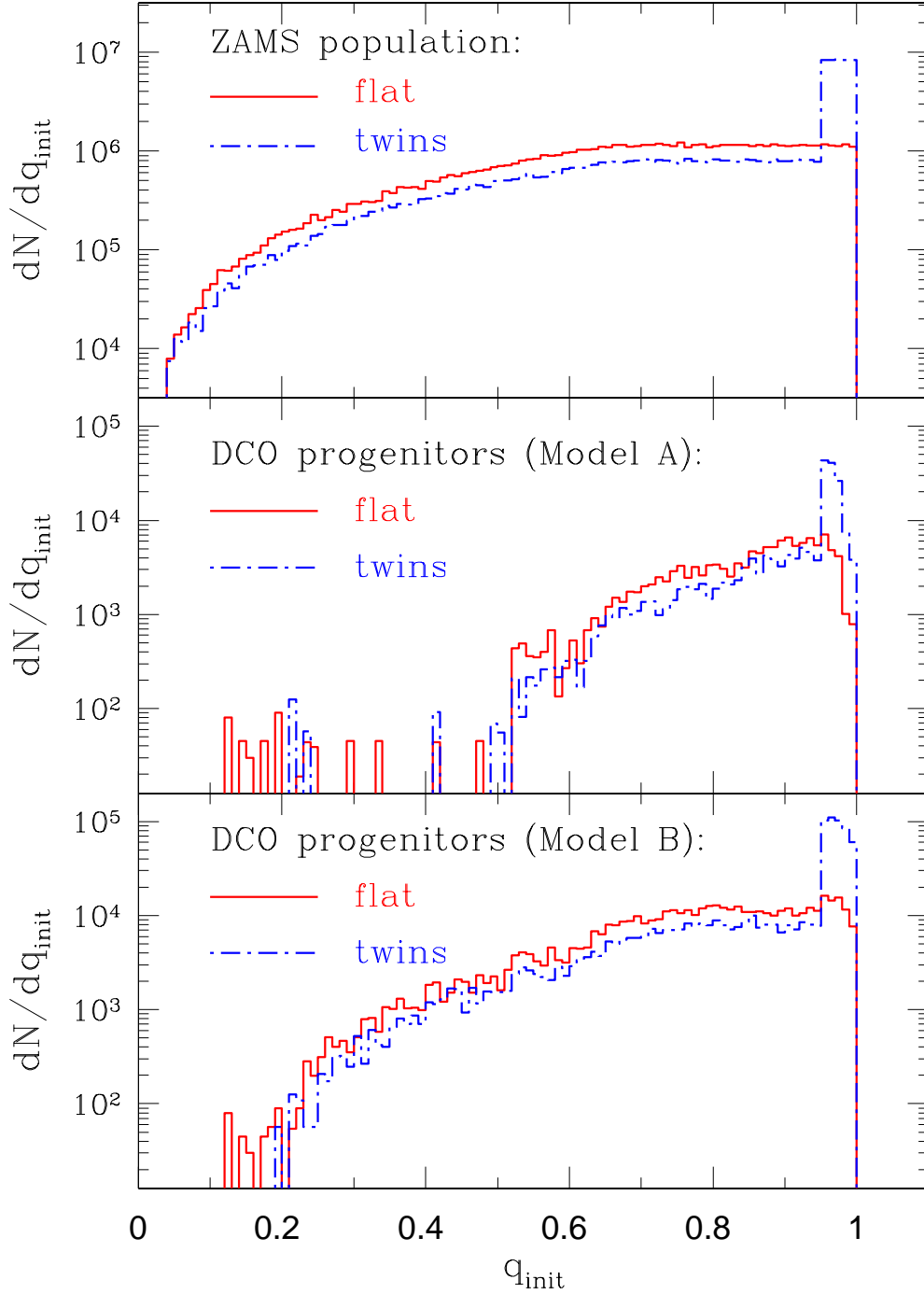


Fig. 1.— Initial mass ratio distribution for Zero Age Main Sequence binaries that we evolve (ZAMS; top panel) and the subpopulation of the above that in the end forms coalescing double compact objects (DCO; bottom panel). We show results of our two calculations: one with an underlying flat mass ratio distribution and the twin one with mass distribution peaked at high q_{init} -values (for details see § 2.3). Note the change of vertical scale from the top panel to bottom panels. The numbers correspond to the entire Galactic population of double compact objects and their progenitors.

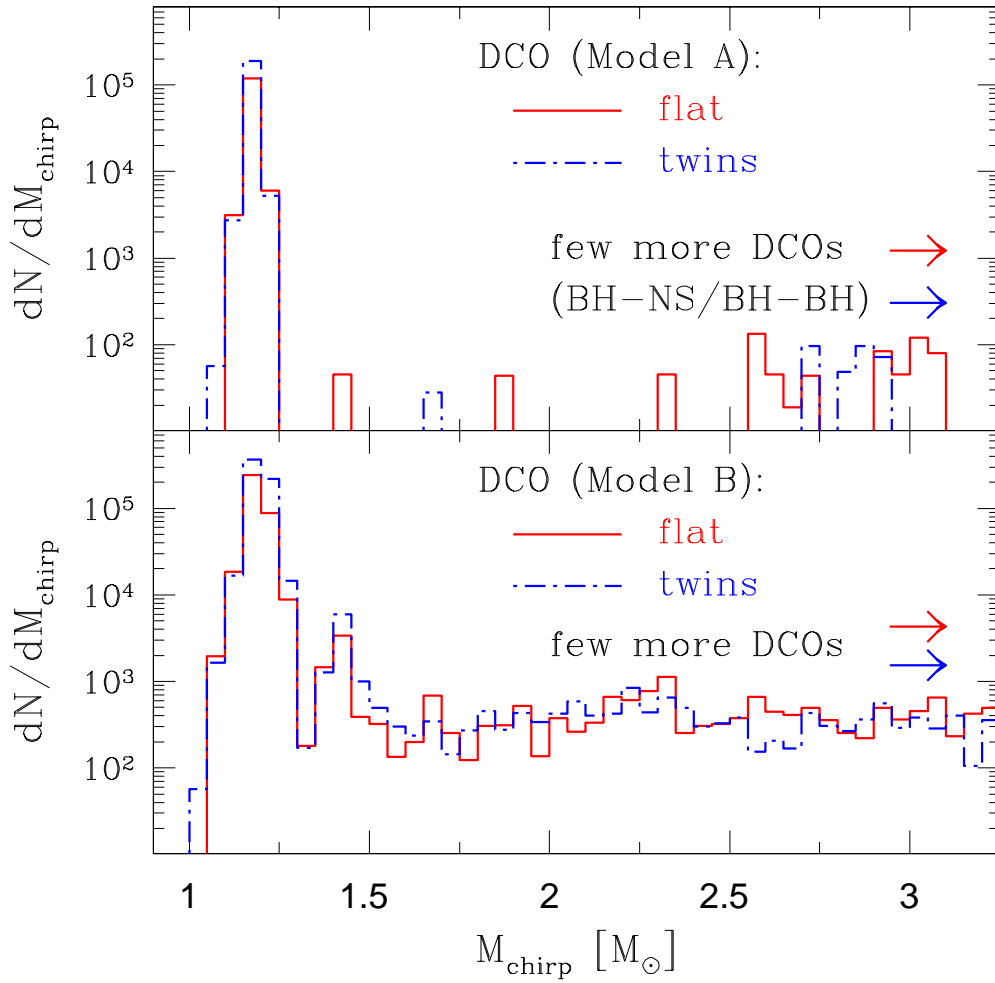


Fig. 2.— Chirp mass distribution for double compact objects for model A (top panel) and model B (bottom panel). Note that the flat and twin population distributions for double neutron stars (majority of DCOs) are almost the same and they peak at $\sim 1.2 M_{\odot}$, while only a small fraction of heavy compact objects (BH-NS and BH-BH binaries) extends to the chirp mass as high as $\sim 10 M_{\odot}$ (not shown).

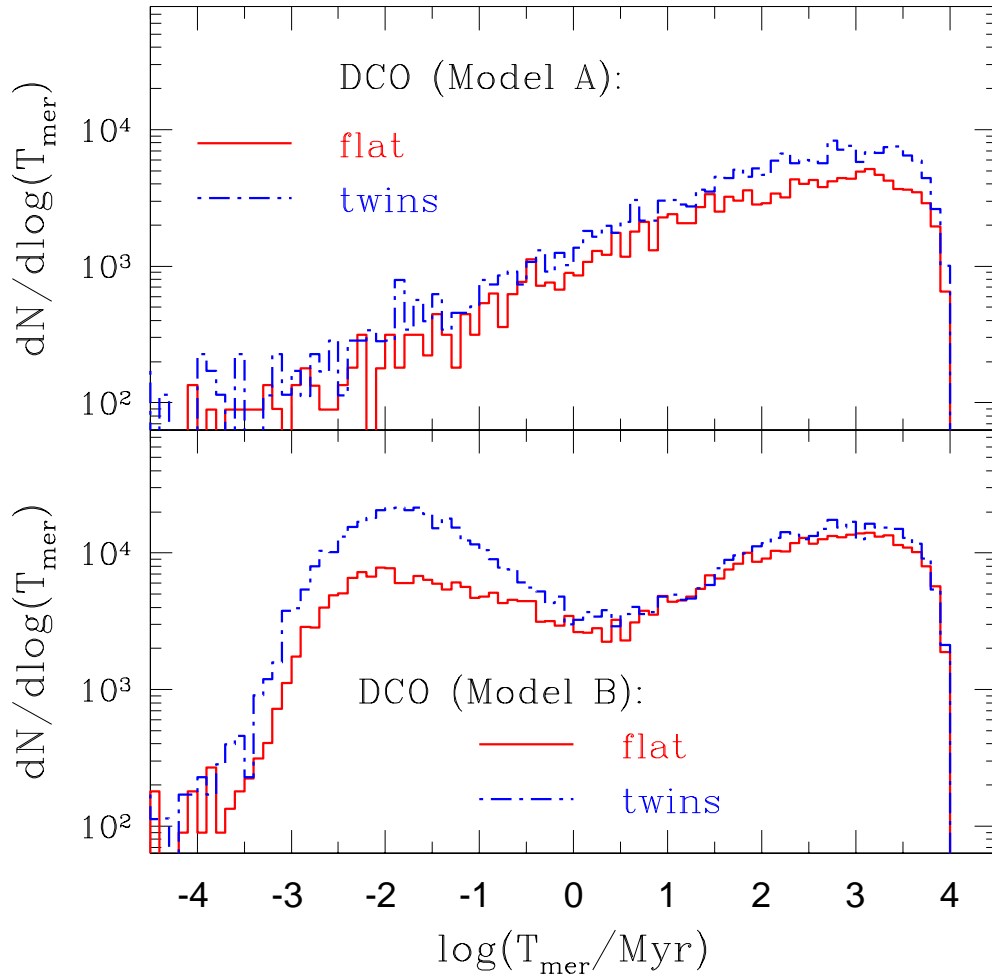


Fig. 3.— Distribution of merger times for double compact objects for model A (top panel) and model B (bottom panel). We can see that twin and flat populations are almost the same for model A and that significant fraction of binaries ($\sim 35\%$) have merger times shorter than 100 Myr. Model B with an alternative approach to common envelope evolution in which we allow survival of systems with Hertzsprung gap donors leads to formation of ultracompact double neutron stars that contribute to the short merger time peak ($T_{\text{mer}} < 1$ Myr). We note that in this model even more: $\sim 60\%$ and $\sim 70\%$ DCOs form with short merger times for flat and twin mass ratio distributions, respectively. The short-lived systems are natural candidates for prompt short-hard GRBs observed in young host galaxies.

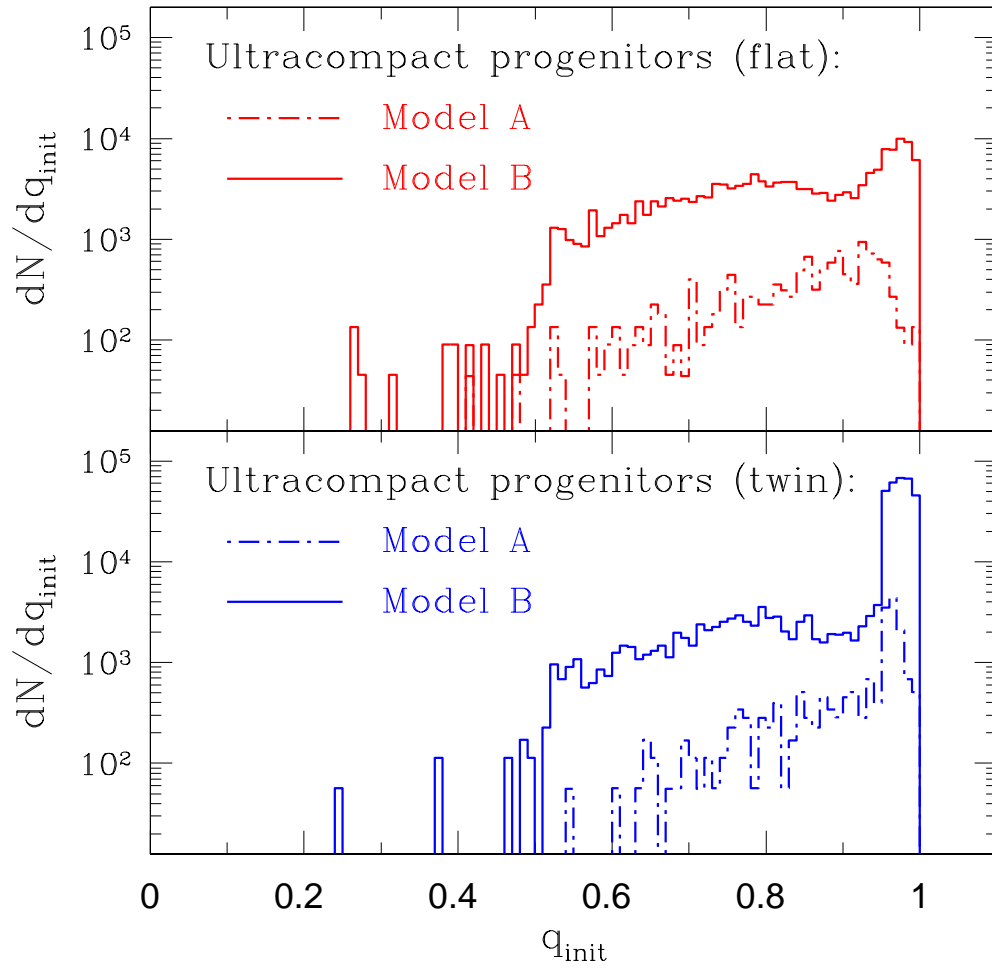


Fig. 4.— Initial mass ratio distribution for Zero Age Main Sequence binaries that evolve into ultracompact DCOs (merger times shorter than 1 Myr). Results are shown for model A and B for both flat (top panel) and twin (bottom panel) populations. For more details see § 3.3.